Technische Universität Berlin

Department of Civil Systems Engineering
Whole Life Civil Systems Analysis WS 23/24
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2nd Assignment (Individual)

Life-Cycle Analysis and Multi-Criteria Decision Making

Multi-purpose Buildings

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Summary

1. Introduction

Continuing the life cycle analysis on my system of interest, a multi-purpose building, during this assignment I am going to conduct a comprehensive life cycle assessment concerning the environmental aspects of the civil engineering system. Essentially, a civil engineering product can undergo life cycle analysis from multiple perspectives, including construction and maintenance costs or energy consumption. However, in this project, the primary focus is on scrutinizing environmental impacts, which are undoubtedly pivotal factors that must be taken into account during the design of every civil engineering product.

The reason lies in the fact that The construction industry is responsible for the unsustainable use of natural resources, and is an important source of air, soil, and water pollution [1]. Published data indicate that this sector uses between 30–40% of primary energy worldwide [2], with these figures including the energy required by the buildings [3,4]. Studies have shown that most of the environmental impacts occur in the production, construction, and the operation phases, representing approximately 80-90% of the total impacts generated in the useful life of the building [5-7].

Hence, the decisions made by engineers and stakeholders during the design phase have both short-term and long-term adverse effects on the environment. It is crucial to meticulously choose the optimal configuration and materials, considering their environmental impacts over both short-term and long-term durations. This selection process should also account for other influential factors that necessitate thorough analysis and discussion in future research.

2. Goal and scope of the assessment

As mentioned in the introduction, this assignment primarily focuses on the detrimental environmental impacts of a multipurpose building. However, the specific objective of this task is to undertake a thorough carbon footprint analysis. Given the intricate nature of building systems comprising multiple subsystems and components, conducting a detailed and comprehensive carbon footprint analysis demands a considerable investment of time and information, which are beyond the scope of this assignment. Consequently, I decided to concentrate solely on a major subsystem rather than attempting an analysis of all subsystems. To achieve this, I chose External Walls as the focal subsystem for scrutinizing its carbon footprint. The scope and the boundaries of the assessment are presented in Figure 1.

The figure presented here is extracted from the research paper titled "Life Cycle Assessment (LCA) of Natural vs Conventional Building Assemblies" conducted by L. Ben-Alon and colleagues, 2021. This paper serves as the main source and inspiration for the current assignment. I will make multiple references to this study in the subsequent sections of the assignment.

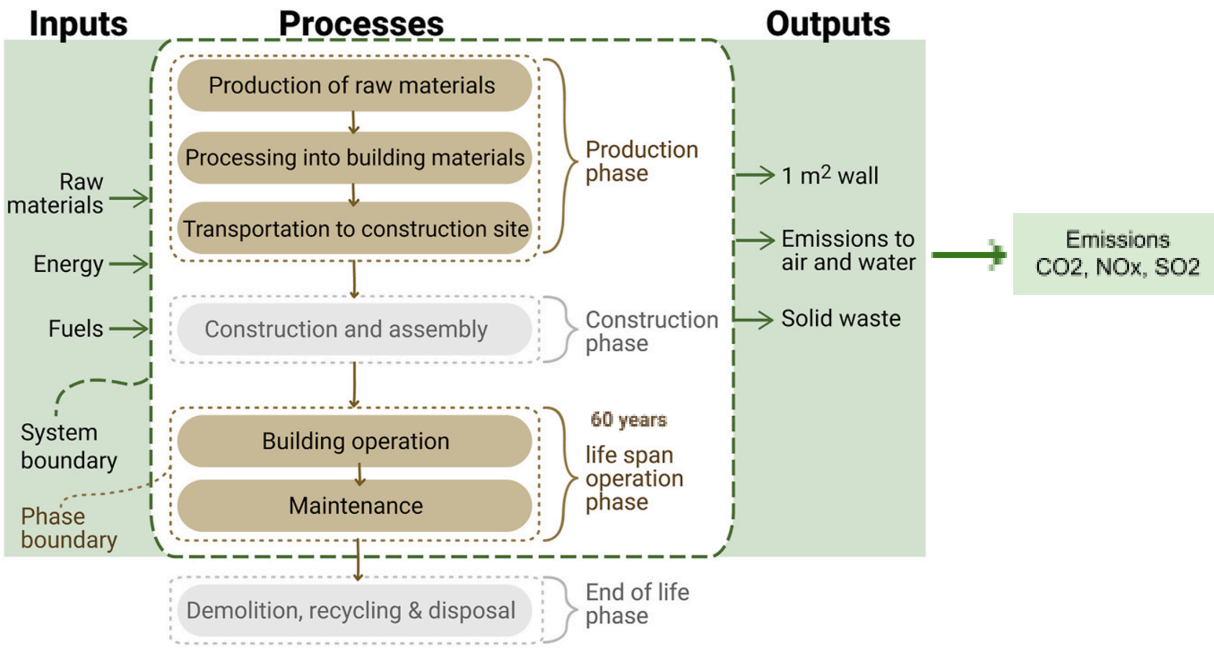

Fig.1. The system boundaries diagram of this life cycle assessment study, L. Ben-Alon, 2021

As it can be seen from the Figure.1, the system boundaries considered extraction and processing of raw materials, manufacture of building materials, transportation to the construction site, and maintenance for a 60-year lifespan of the building. Onsite construction as well as demolition and disposal energy and emissions are beyond the system. Essentially, the amount of energy, fuel, and emissions will be calculated for a 1 m2 of external walls.

The scope of this study encompasses deciding on the external walls (EWs) of buildings with a maximum height of three stories, catering to a variety of functions, including residential, educational, commercial spaces, and offices. However, it excludes EWs for other building types such as industrial buildings that are subject to specific regulations.

3. Design options

To make informed decisions on diverse design alternatives, I conducted extensive background research, specifically delving into various configurations for external walls and their corresponding life cycle inventories (LCI). Drawing substantial inspiration from the study conducted by L. Ben-Alon in 2021, I opted to conduct a comparative analysis between two distinctly different material categories: earthen and bio-based materials on one hand, and conventional materials used in configuring the building's external walls on the other. This decision was motivated by the unique features of earthen materials, which were historically prevalent but have now been marginalized in favor of modern materials characterized by high raw material demand and energy consumption in production.

In contrast with other building materials, earthen and bio-based materials exhibit a number of advantages: a) high thermal inertia and structural capacity in compression; b) a better resistance to fungi, insects and rodents, compared to exposed cellulose-based materials; c) potential abundance in and around the construction site; d) a diversity of building forms and construction techniques, from sculptural monolithic assemblies to modular components [8]. Additionally, the advantages of earthen assemblies as a thermal mass can be used in cold climates by placing it within an insulated envelope or by using Trombe walls; the assembly can store and retain heat from passive solar or active indoor sources and release this heat slowly over a period of time (e.g., over a cold night) [8,9].

Considering these numerous environmental and health benefits, I will perform the comparison between two natural building assemblies (light straw clay and insulated rammed earth) to conventional building assemblies (insulated wood frame, and insulated concrete masonry units). Figure. 2, illustrates all four types of wall configurations analyzing in this study.

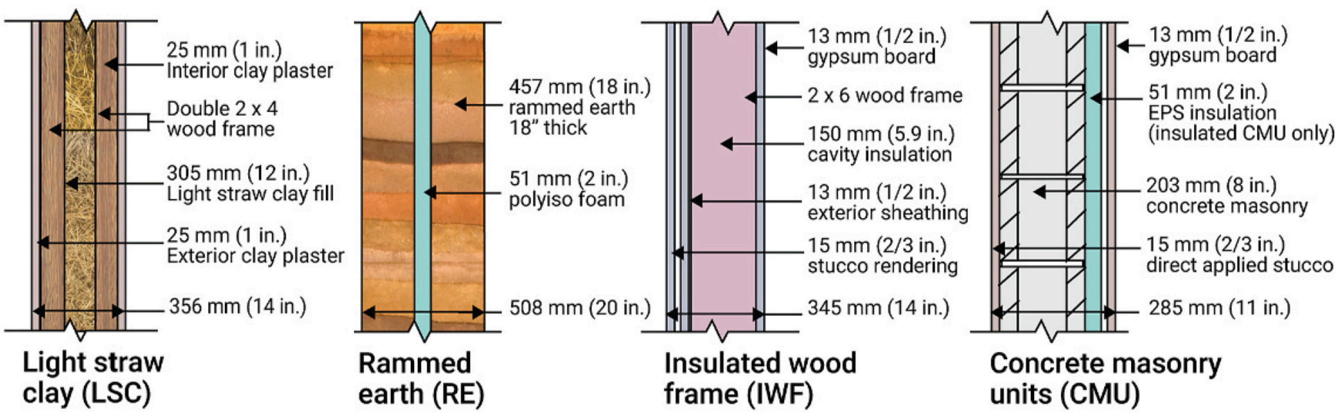

Fig.2. Section drawings of the assessed wall systems, L. Ben-Alon, 2021

Each of the wall systems included in this LCA were analyzed according to the constituent materials, as detailed in the following subsections.

3.1. Light Straw Clay (LSC)

The light straw clay wall section, illustrated in Fig. 2a, was designed based on the IRC light straw clay appendix [10]. The incorporated section includes light straw clay infilling a 38 × 89 mm (2 × 4 in.) double stud timber frame as described in section AR103.2.4 in Ref. [10]. The overall core density of the 305 mm (12 in.). Additionally, in order to make the comparison more realistic and enhance the thermal performance I added an extra layer of insulation EPS R15 51mm.

3.2. Insulated Rammed Earth (IRE)

The rammed earth wall section, illustrated in Fig. 2b, was designed according to common practice and code requirements [11,12]. Rammed earth mainly requires clay-rich soil, sand and gravel, with no added fiber, to which a small amount of water is added to achieve optimal compaction. This study assumed 20% gravel and 8% water content [13]. Additionally, the 457 mm (18 in.) a thick rammed earth wall was assumed to have no plaster, which is the common practice to achieve the desirable aesthetic effect of rammed earth components. A variation of the plain rammed earth wall section also considered was insulated rammed earth (IRE) into which 51 mm (2 in.) R-12 polyisocyanurate (polyiso) insulation was added at the midplane of the wall.

3.3. Insulated Wood Frame (IWF)

The conventional wood frame wall system, illustrated in Fig. 2c, was selected to represent a typical light-frame wood wall section [14]. The wall included the following layers, listed from interior to exterior: 13 mm (0.5 in.) gypsum board, 38 × 140 mm (2 × 6 in.) dimensional lumber, cavity insulation in the form of a 150 mm (5.9 in.) R-21 fiberglass batt 13 mm (0.5 in.) plywood sheathing, and 15 mm (0.6 in.) stucco.

3.4. Insulated Concrete Masonry Units (ICMU)

The benchmark concrete masonry unit (CMU) system, illustrated in Fig. 2d, was selected from Ref. [15]. The CMU wall included the following layers, listed from interior to exterior: 13 mm (0.5 in.) gypsum board, 203 mm (8 in.) CMU blocks, and 15 mm (0.6 in.) Portland cement-based stucco, 51 mm (2 in.) of R-15 extruded polystyrene insulation between the CMU and interior gypsum board.

4. Life cycle inventory of different materials

To achieve the amount of environmental indicators for each of the materials, I used the findings of the L. Ben-Alon study which are represented in Figure. 3.

Inventory item		Straw	Sand/ gravel	Clay-rich soil	Clay plaster	Tap water	Lumber	Gypsum board, 13 mm	CMU blocks	Portland cement stucco, 60 mm	Plywood, 13 mm	Fiberglass batt, R21	EPS insulation, R15, 51 mm
	units	/bale	/kg	/kg	/m^2	/kg	/m^3	/m^2	/100 ct	/m^2	/m^2	/m^2	/m^2
coal	MJ	2.14	0.0205	0.0012	1.14	0.0030	240	–	481	2.91	–	0.72	26.4
natural gas	MJ	11.4	0.0105	0.0108	2.57	0.0015	796	28.6	109	10.30	4.95	3.69	121
oil	MJ	11.8	0.0619	0.0876	8.02	0.0008	329	9.80	1	0.47	–	0.42	117
diesel	MJ	–	–	–	–	–	–	8.89	279	1.38	12.2	–	–
electricity	MJ	–	–	–	–	–	–	2.92	137	1.79	25.7	55.6	–
other	MJ	0.07	0.0027	0.0177	–	0.0006	–	–	219	0.40	0.75	–	–
total	MJ	25.3	0.0956	0.1170	11.70	0.0058	1366	50.2	1225	17.2	43.6	60.5	265
CO_2	kg	0.85	0.0042	0.0070	0.428	0.0004	52	2775	0.39	2628	2.80	15.3	9.98
SO_2	kg	0.0060	2.9e-6	6.1e-6	0.0004	1.7e-6	0.342	8.08	0.523	2.21	–	0.0014	0.0816
NO_x	kg	0.0116	3.6e-5	3.7e-5	0.0030	1.0e-6	0.288	11.4	0.0222	11.2	0.0452	0.0586	0.0371
VOC	kg	2.4e-5	9.4e-7	1.0e-5	6.6e-5	3.1e-10	0.054	1.77	0.0080	0.196	–	0.0096	0.0002
CH_4	kg	0.0035	4.0e-6	4.2e-6	0.0004	2.3e-13	0.173	0.324	0.226	0.052	0.0136	0.0069	0.0027
CO	kg	0.0007	2.3e-5	3. 9e-5	0.0023	3.0e-7	0.114	3.94	0.748	1.08	–	0.0348	0.0207
TPM	ppm	0.0004	2.2e-6	3.5e-7	0.0004	1.6e-6	0.366	6.39	0.390	4.12	–	0.0005	0.0061

Fig.3. Life cycle inventory results for each constituent material, L. Ben-Alon, 2021

Table 1 provides a summary of the life cycle inventory for all the materials in the design alternatives, along with the calculated quantities of material required to create and construct one square meter of wall. The units of energy and emissions are MJ and kg, respectively. These values are calculated for each material based on their respective units.

Material	Scope	Quantities*	Energy (MJ)	CO2 (kg)	NOX (kg)	SO2 (kg)
Straw	LSC	2	25.3	0.85	0.0116	0.006
Timber stud	LSC	0.011	1366	52	0.288	0.342
Clay plaster	LSC	2	11.7	0.428	0.003	0.0004
EPS insulation R15	LSC	1	265	9.98	0.0371	0.0816
Clay rich soil	IRE	429	0.017	0.007	3.70E-05	6.10E-06
Sand and Gravel	IRE	118	0.0956	0.0042	3.60E-05	2.90E-06
Water	IRE	47	0.0058	0.0004	1.70E-06	1.00E-06
EPS insulation R15	IRE	1	265	9.98	0.0371	0.0816
Clay plaster	IRE	2	11.7	0.428	0.003	0.0004
Gypsum board	IWF	1	50.2	2775	11.4	8.08
Timber stud	IWF	0.017	1366	52	0.288	0.342
Fiberglass batt R21	IWF	1	60.5	15.3	0.0586	0.0014
Plywood sheathing	IWF	1	43.6	0	0.0452	0
Stucco rendering	IWF	1	17.2	2628	11.2	2.21
Gypsum board	ICMU	1	50.2	2775	11.4	8.08
Stucco rendering	ICMU	1	17.2	2628	11.2	2.21
EPS insulation R15	ICMU	1	265	9.98	0.0371	0.0816
CMU blocks	ICMU	0.6	1225	0.39	0.0222	0.523

Table. 1.Summary of the life cycle inventory for all the constituent materials

* The quantity column represents the material needed for one square meter of each wall configuration.

5. Life-Cycle Timeline

As mentioned earlier, this study also considers the environmental impacts of the system throughout its service life, including the effects of maintenance interventions. To perform this, I conducted an extensive literature review. Unfortunately, there is limited information and studies available regarding natural and earthen wall sections, highlighting the need for further research in this area. In the life cycle assessment of natural vs conventional building assemblies, L. Ben-Alon makes suggestions for necessary maintenance interventions for both natural and conventional external wall configurations based on references. These recommendations aim to maintain the functionality of building walls until the end of their life span.

Furthermore, I incorporated the findings from a study conducted by André Petersen at the University of Lisbon, titled 'Service Life Prediction of Painted Renderings Using Maintenance Data through Regression Techniques' in 2014. The relevant information is presented in Figures 4 and 5.

Periodic-ity	Maintenance actions	Cost in year 0 (€/m^2)	Current cost (€/m^2)	Present-value cost (€/m^2)
15 years	Scaffolding	6.30	146.36	46.14
	Façade cleaning (mechanical with water jet)	12.79		
	Crack repair (from 0.5 mm to 2 mm wide)	22.57		
	Repair of loss of cohesion of the rendering	14.49		
	Treatment of efflorescence, surface dirt, stains and biological growth	14.09		
	Repainting with plastic paint	11.03		
20 years	Scaffolding	6.30	145.45	31.20
	Rendering removal	4.22		
	Substrate cleaning and repair	15.5		
	Application of rendering (pre-mixed)	29.33		
	Painting (plastic paint)	11.03		
10 years	Scaffolding	6.30	63.04	29.20
	Façade cleaning (mechanical with water jet)	12.79		
	Crack repair (up to 0.5 mm wide)	12.47		
	Repainting with plastic paint	11.03		
20 years	Scaffolding	6.30	145.45	31.20
	Rendering removal	4.22		
	Substrate cleaning and repair	15.5		
	Application of rendering (pre-mixed)	29.33		
	Painting (plastic paint)	11.03		

Fig.4. Periodicity suggestion made by A.Petersen colleagues associated with building's external walls, 2014

Characteristics	Sub-factor	Estimated service life (years)	Ratio between estimated service life and reference service life	Increase/decrease of the estimated service life according to the degradation factors (%)
Type of product	Smooth paints	Non-conclusive	Non-conclusive	Non-conclusive
	Textured paints			
	Plastic membranes			
Paint finish	Rough	9.8	1.005	+0.5%
	Smooth	9.4	0.964	-3.6%
Paint colour	White	Non-conclusive	Non-conclusive	Non-conclusive
	Yellow, orange and light pink			
	Light green and blue, dark pink			
Surface preparation	Repainting over previous paint coat	9.9	1.015	+1.5%
	Paint over rendering	9.7	0.995	-0.5%
Exposure to humidity	Unfavorable	9.3	0.954	+4.6%
	Current	10.0	1.026	+2.6%
Distance from the sea	Less than 1 km	9.2	0.944	-5.6%
	Between 1 km and 5 km	9.4	0.964	-3.6%
	More than 5 km	10.0	1.026	+2.6%
Wind-rain action	Slight	10.1	1.036	+3.6%
	Moderate	9.6	0.985	-1.5%
	Severe	9.4	0.964	-3.6%
Façade orientation	North	10.2	1.046	+4.6%
	South	9.1	0.933	-6.7%
	East	10.1	1.036	+3.6%
	West	9.1	0.933	-6.7%

Fig. 5. Estimated service life suggested by A.Petersen colleagues associated with building's external walls

Additionally, I leveraged the insights gained from the study 'Condition-Based Maintenance Strategies to Enhance the Durability of ETICS' conducted by C. Ferreira in 2021. This study specifically focuses on analyzing the impact of various maintenance strategies to improve the lifespan of building walls employing External Thermal Insulation Composite Systems (ETICS).

A summary of the considered maintenance interventions is provided in Table 2.

Design Option	Event	Frequency	Total life span
1.Light Straw Clay (LSC)	EC*	5	60
1.Light Straw Clay (LSC)	CR*	10	60
1.Light Straw Clay (LSC)	PR*	15	60
2.Insulated Rammed Earth (IRE)	EC	5	60
2.Insulated Rammed Earth (IRE)	CR	10	60
2.Insulated Rammed Earth (IRE)	PR	15	60
3.Insulated Wood Frame (IWF)	EC	5	60
3.Insulated Wood Frame (IWF)	CR	10	60
3.Insulated Wood Frame (IWF)	PR	20	60
4.Concrete Masonry Units (CMU)	EC	5	60
4.Concrete Masonry Units (CMU)	CR	10	60
4.Concrete Masonry Units (CMU)	PR	20	60

Table. 2. Summary of the maintenance interventions for four design alternatives

*EC: External Cleaning, CR: Component Repair, PR: Partial Replacement

Additionally, Figures. 6-9, illustrate sketches of above mentioned maintenance interventions using the web application Shiny.

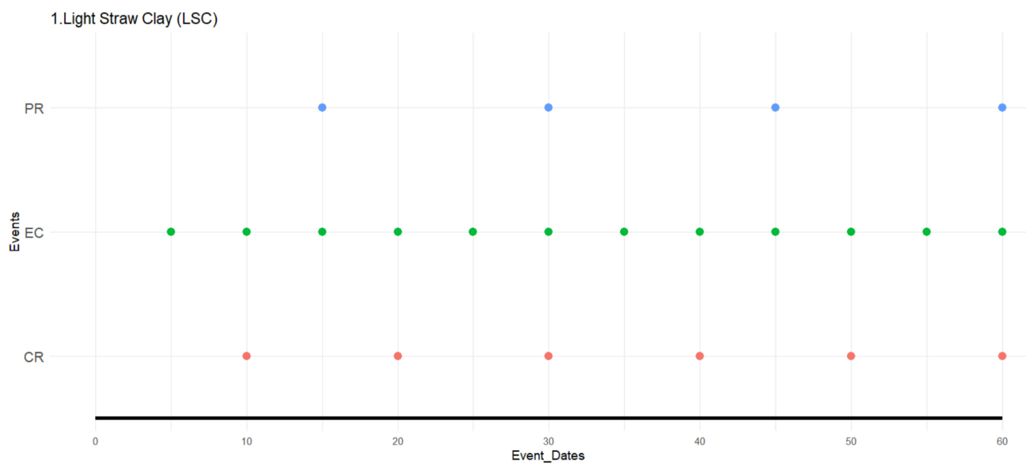

Fig. 6. Maintenance interventions for light straw clay wall system during building's life span

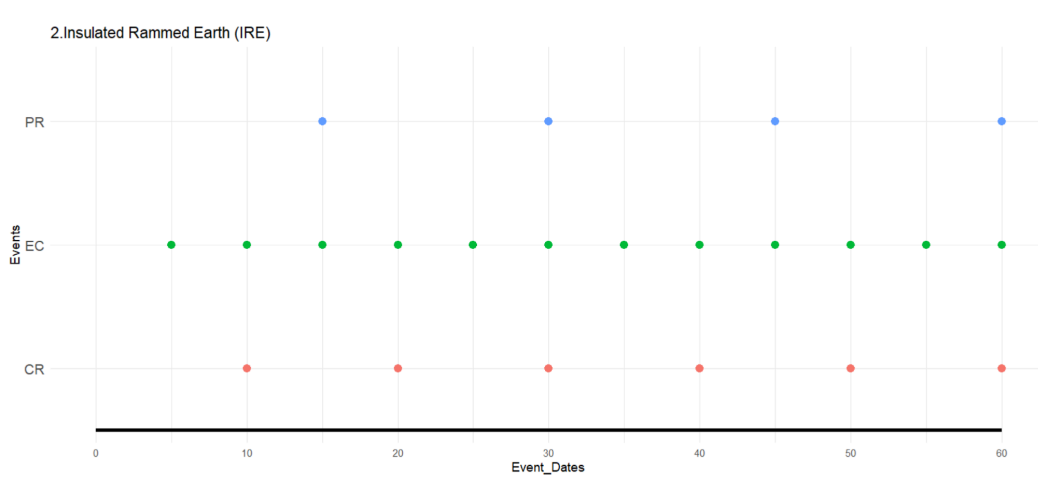

Fig. 7. Maintenance interventions for insulated rammed earth wall system during building's life span

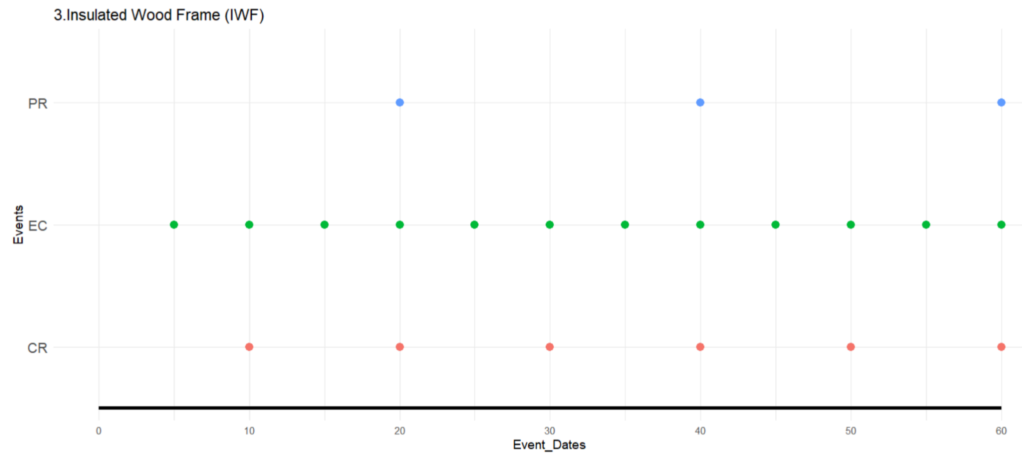

Fig. 8. Maintenance interventions for insulated wood frame wall system during building's life span

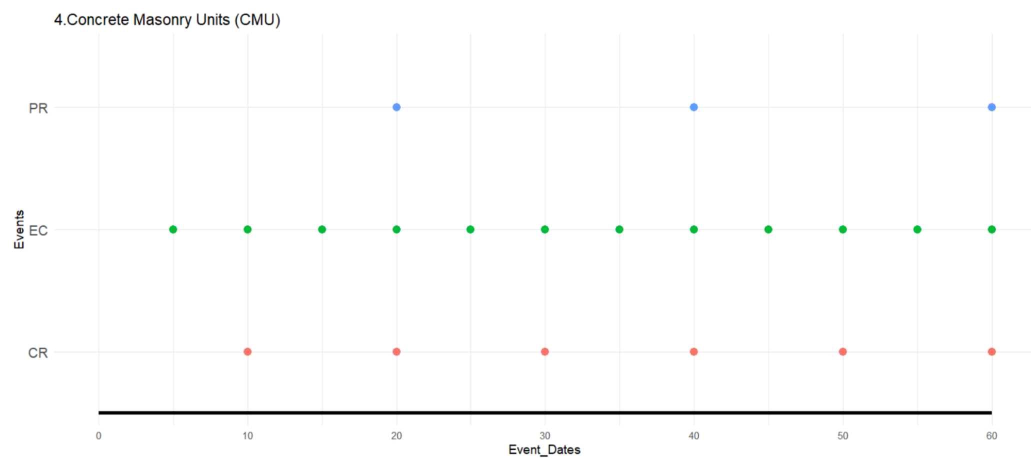

Fig. 9. Maintenance interventions for insulated concrete units wall system during building's life span

6. Discussion and results

6.1. Life Cycle Analysis

6.1.1. Energy

Building upon the information collected and calculated in the previous section, I performed the life cycle analysis for suggested design options, utilizing the capabilities of the R software. Figures 10-14 illustrate the amount of energy and emissions individually. In the subsequent section, the effects of these environmental indicators will be combined using the Multi Criteria Decision Making (MCDM) method.

As it can be seen from the Figure. 10, design option 4 which is our concrete based design option with more than 2000 MJ per one square meter has the highest amount of energy. Surprisingly, light straw and rammed earth walls, which are our bio-based design option, ranks second and three, respectively, in the energy section even though they used only natural and earthen materials. It indicates that using the natural and bio-based materials cannot ensure a low level of energy in production and maintenance of these configurations. Another important reason for this high level of energy for these two options is for higher frequency maintenance interventions compared to conventional options. Indeed, they might require less energy in the production phase, but their high maintenance demand increases the accumulated energy during the system life span. Meantime, wood frame wall design with approximately 400 MJ has the best performance in this section and among the design options.

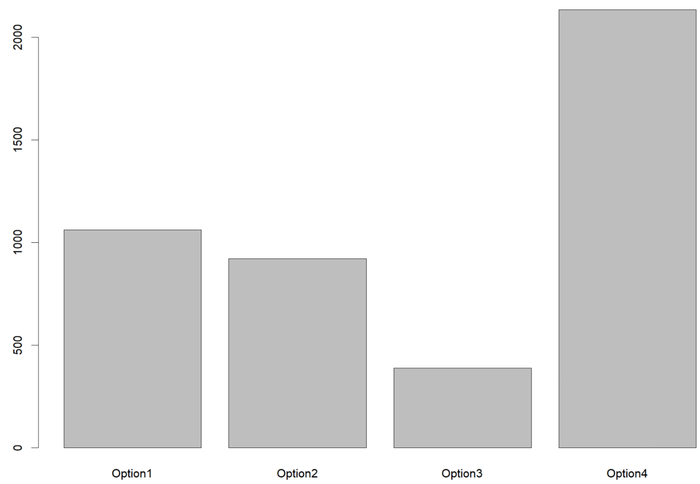

Fig. 10. Energy consumption for one square meter of various design options, (unit, MJ)

6.1.2. Emissions, CO2, NOx, and SO2

Unlike energy usage, the emissions are significantly higher for conventional design options, as evident in Figures 11, 12, and 13. While the emissions for the two natural design options are close to zero, both conventional options exhibit relatively higher values.

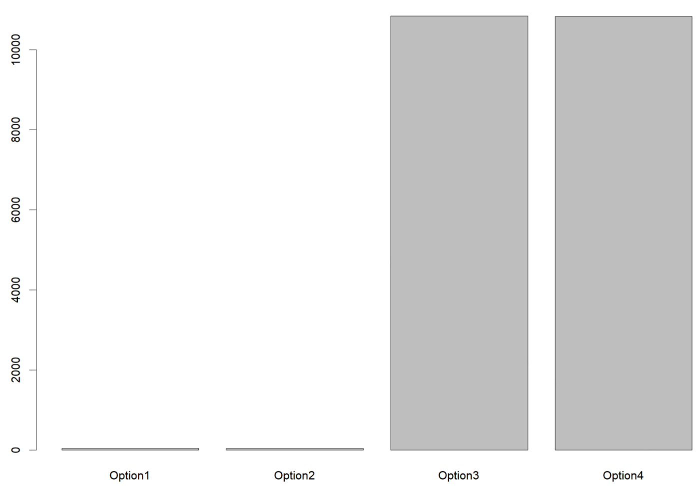

Fig. 11. CO2 emission for one square meter of various design options, (unit, kg)

In terms of the CO2 emission diagram, both wood frame and concrete-based walls release approximately 11,000 kg of CO2 per square meter of wall. Similarly, they emit 50 kg of NOx per square meter of wall. However, in terms of SO2 emissions, the concrete masonry wall releases slightly more with 30 kg compared to the wood frame wall, which emits 20 kg per square meter.

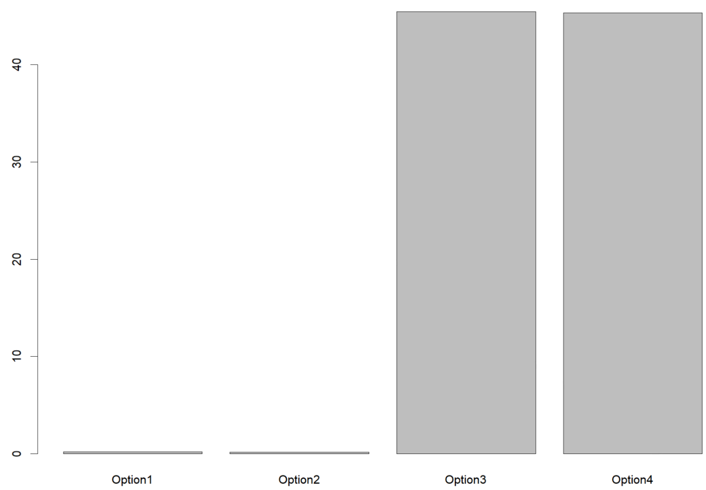

Fig. 12. NOx emission for one square meter of various design options, (unit, kg)

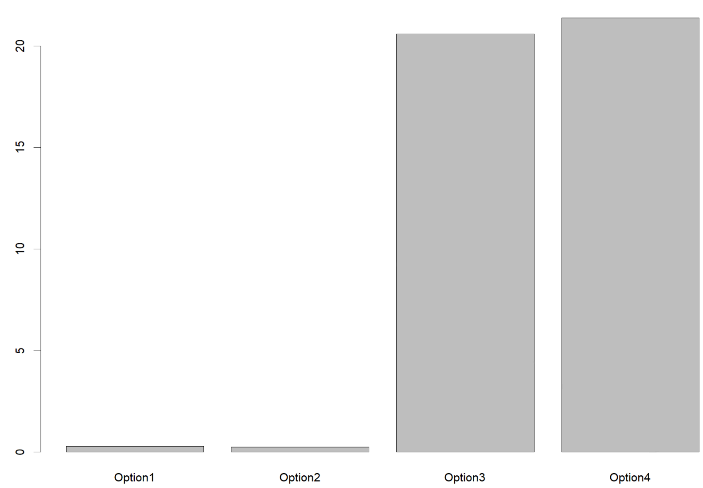

Fig. 13. SO2 emission for one square meter of various design options, (unit, kg)

7. MCDM – Analytic hierarchy process (AHP)

In the previous section we analyzed the values for each of the environmental indicators independently. This is while in reality we need to see and analyze the effects of all the influential effects together to be able to make informed decisions. To achieve this, in the final section, we establish the analytic hierarchy process (AHP) to see the integrated effect of all our multi criteria based on their importance. Figure 14, represents the result of the multi criteria decision making process. It can be clearly seen that option number 1 has the highest score with nearly 50%, followed by the other natural design option with 32,4 %. Concrete masonry wall also has the lowest score standing less than 5.

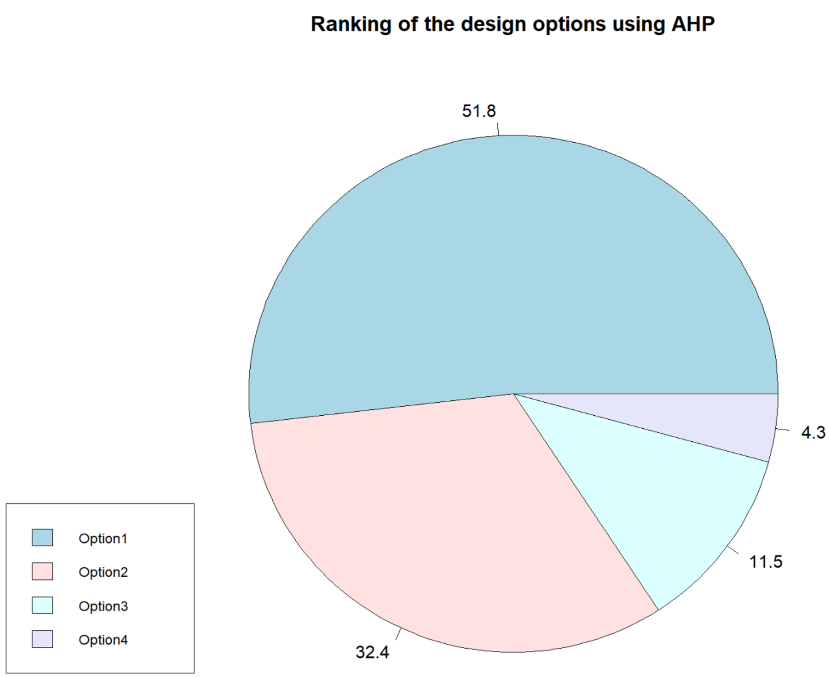

Fig. 14. Analytic hierarchy process results

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